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EF-6 A Kinematically Beamed, Low Energy Pulsed Neutron Source for Active Interrogation

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Abstract

We are developing a new active interrogation system based on a kinematically focused low energy neutron beam. The key idea is that one of the defining characteristics of SNM (Special Nuclear Materials) is the ability for low energy or thermal neutrons to induce fission. Thus by using low energy neutrons for the interrogation source we can accomplish three goals, 1) Energy discrimination allows us to measure the prompt fast fission neutrons produced while the interrogation beam is on; 2) Neutrons with an energy of approximately 60 to 100 keV do not fission 238U and Thorium, but penetrate bulk material nearly as far as high energy neutrons do and 3) below about 100keV neutrons lose their energy by kinematical collisions rather than via the nuclear (n,2n) or (n,n') processes thus further simplifying the prompt neutron induced background. 60 keV neutrons create a low radiation dose and readily thermal capture in normal materials, thus providing a clean spectroscopic signature of the intervening materials. The kinematically beamed source also eliminates the need for heavy backward and sideway neutron shielding. We have designed and built a very compact pulsed neutron source, based on an RFQ proton accelerator and a lithium target. We are developing fast neutron detectors that are nearly insensitive to the ever-present thermal neutron and neutron capture induced gamma ray background. The detection of only a few high energy fission neutrons in time correlation with the linac pulse will be a clear indication of the presence of SNM.

Introduction

There are many possible scenarios for active interrogation of commercial cargo. Compared to a classic nuclear physics laboratory environment, cargo scanning has to deal with an enormous range in both the amount and makeup of attenuating or shielding materials. This gives rise to a formidable problem of background discrimination making cargo inspection a very different problem from measurements designed to measure nuclear properties in a clutter free controlled environment. The main problem is the enormous thickness and variety of the possible intervening material, approaching the thickness of nuclear reactor shielding walls. For some scenarios, either gamma rays or neutrons cannot penetrate the cargo efficiently. On the other hand, it is very difficult to shield both gamma (or X-rays) and neutron penetration at the same time when there is a limit on the weight of the shielding. For gamma rays, heavy elements are difficult to penetrate, for neutrons, light elements like plastic and water are difficult. The most promising detection method that we can create is a combination of 3 different methods to cover all possible scenarios:

1) Unshielded SNM like Uranium 235 (mixed with U238) or Pu239 and other SNM materials are easily detected by passive radiation measurement with large gamma ray scintillation detectors and neutron detectors.
2) Heavily shielded SNM in a low Z neutron absorbing overburden is easily observed with a high energy X-ray scan of the cargo, (preferably 2-axis and two different X-ray energies for better material identification, like the luggage scanners used in airports). The detection of a heavy and very dense object in the middle of a large amount of

hydrogenous material will be very suspicious and is usually not encountered in normal shipping containers.

3) Active neutron interrogation of a container without a large amount of homogeneously distributed hydrogenous material can unmistakably detect the presence of SNM and serve to remove all confusion in interpretation of complex radiographs. The active interrogation needs to be exclusively sensitive and specific to SNM like 235U or 239Pu, and not confused by passive materials like Thorium, which is present in many materials at a significant level. The return signal of the active interrogation has to be unique to the presence of SNM, and should produce no signal from the many tons of "inert" material present in a typical container.

Concept Description

There is one unique method of interrogation which is very specific to SNM and produces an essentially background free return signal. Sending out low to medium energy neutrons in the energy range between 10 and 200 keV, and observing the induced 1 to 5 MeV fission neutrons from SNM with detectors able to discriminate between photons, fission neutrons and interrogating neutrons.

This method produces a nearly background free identification signal for SNM. Even a small number of detected fast neutrons will be a positive signal, since the fast neutron background from natural sources is very low.

The neutron source

Our source of medium energy neutrons is the (p,n) reaction of a 2 MeV proton beam on a 7-Li target[1,2]. Since the early days of nuclear physics it has been known that one can produce medium energy neutrons with the ^{7}Li(p,n) reaction. But since there was little physics use for a medium energy neutron source, this reaction was rarely used and very few accelerators have been built to make use of this reaction. The reaction has a threshold of 1.88 MeV and the cross section rises to its full value within 20 keV of the threshold proton beam energy. It is a very sharp threshold reaction. If one chooses a proton beam energy just above the reaction threshold, it is possible to restrict the neutron emission pattern to a 60-degree forward cone. The kinematics of this reaction produces a forward directed neutron beam. There are no neutrons emitted backwards from the target and the opening angle is controlled by the proton beam energy. The higher the proton beam energy above threshold, the wider the opening emission angle will be. The narrow opening angle reduces the neutron activation of the surrounding facilities dramatically. There is also no need for bulky and heavy neutron shielding in order to "collimate" the beam. Having no need for bulky shielding, one can place the fast neutron detectors rather close to the accelerator and target. Since the outgoing neutrons have rather low energy, the radiation dose delivered to the cargo is lower than an equivalent number of higher energy neutrons and useable beams do not pose a threat to equipment or humans in the cargo.

Neutron production rates can be as high as 10^{10} per second into a 1 steradian cone, equivalent to a ten times higher strength source emitting into 4π. With a strong source, one can scan a complete cargo container in much less than 1 minute. The 2 MeV proton accelerator is less than half the size of a typical office desk, is portable, plugs into a regular electrical outlet and requires no cooling water. There is the possibility to build a very tightly focused neutron beam by reversing the ^{7}Li(p,n) reaction to ^{1}H(^{7}Li,n). The benefit is a very narrow and high brightness neutron beam, the drawback is that the accelerator to produce 14 MeV ^{7}Li is much larger and much more expensive.

Fast neutron detection

The fast neutron sensitive detectors are a key to the nearly background free detection of SNM. Sending out a high flux of neutrons into a random cargo will produce significant gamma radiation, since most neutrons will eventually be captured resulting in the emission of very energetic gamma rays. The typical neutron capture reaction releases about 7-8 MeV of gamma ray energy. The detector has to be able to distinguish between the gamma rays and the energetic neutrons. Discriminating liquid scintillator detectors were developed many years ago, and the pulse shape discriminating read-out electronics has been steadily improved in the last 20 years. The development was mainly driven by the development of low background detectors for deep underground astro-physics instruments.

Gamma ray – neutron discrimination

Gamma ray - neutron discrimination is a strong function the actual count rate in the detector, so it is beneficial to keep the absolute count rate rather low to eliminate loss of discrimination due to pileup. Our current detector array is segmented to keep the individual detectors to less than 1-liter volume per element and are about one square meter in total surface area.. Arrays on each side of the neutron source and a few on the opposite sides of the container will be sufficient. Our tests have shown that we have near zero background in our fast neutron detectors, even while the interrogating neutron beam is on. This makes it possible to detect SNM with only a few tens or hundreds of counted high-energy fission neutrons. We currently employ a clever analog electronic circuit to distinguish the pulse shapes, but it performance degrades at high-count rates. A fully digital readout will practically eliminate this problem and give a much cleaner neutron signal, even in a high gamma rate environment. We plan to quantitatively assess the improvement in overall system sensitivity by implementing a digital event readout system.

Neutron diffusion

The free path length of fast neutrons in most materials is rather short, typically between 2 and 5 cm. The free path length between elastic scatterings is surprisingly independent of atomic mass, making most materials look the same for neutron penetration. Neutrons can scatter for many meters in heavy material before they thermalize and are ultimately captured. An important exception is hydrogenous material like polyethylene or water. Neutrons lose some energy in every collision; the typical loss is proportional to the atomic weight ratio of the neutron and the scattering nucleus. Thus, neutrons lose their energy comparatively fast in materials with a significant fraction of hydrogen, like water or polyethylene. In water, the useful diffusion depth is about 30 cm. In heavy materials, a container full of tools or electronics is not an obstacle.

The 60 keV neutrons will have a useful penetration depth comparable to a multi-MeV neutron beam in non- hydrogenous materials. This is because most of the diffusion length comes from the random walk of the ever-slowing neutrons at lower energies. The energy loss is an exponential process, so very energetic neutrons rapidly slow down to medium energies, and then undergo the same diffusion processes as the 60 keV neutrons. At higher energies, there is also an extra contribution to the energy loss mechanism since fast neutrons lose much of their energy by inelastic excitation of the target nuclei, producing unwanted additional gamma radiation.

Thermalized neutrons will cause much of the fission of SNM in a cargo container, where the fission cross-section is very large for 235U and 239Pu. The fast fission neutrons with an average energy of 2 MeV have to be able to exit the container, reversing the path of the interrogating neutrons. Only neutrons that do not lose too much energy on their way out can be counted, since the area is flooded with low energy interrogating neutrons.

Modeling the neutron penetration

Most neutrons will scatter in the cargo material until the neutron reaches thermal energy, and then they undergo a capture reaction. Most bulk materials with very few exceptions have very small capture cross-sections for energetic neutrons. The elastic scattering energy loss mechanism depends strongly on the atomic mass of the material; in non-hydrogen bearing material it takes hundreds or thousands of scattering reaction to reach thermal neutron energies. The long random walk path of the neutron allows it to diffuse up to 1 meter without severe attenuation. If large amounts of hydrogen are present, the neutrons can lose their energy much faster and the penetration depth is reduced. But even fast neutrons lose part of their energy in the first few collisions and then follow the same path as lower energy neutrons.

The penetration depths for different materials and energies were modeled with the Monte Carlo code MCNP. We used semi-infinite slabs of polyethylene, borated polyethylene, aluminum, and iron, with neutron energies of 0.06, 2.0, and 14.0 MeV impinging at normal incidence (see Table 1). The neutrons were transported until they either escaped or were lost through capture. The simulations showed large (few meters) penetration depths for aluminum and iron slabs almost independent of neutron energy. On the other hand, we noticed significant differences in the penetration depths for hydrogenous materials. Due to the large proton cross section at thermal and intermediate neutron energies, the effective penetration depth of 0.06 MeV neutrons is limited to ~ 20 cm.

Table 1, Penetration depths (defined as the depth reached by 1 % of incident neutrons).

	E = 0.06 MeV	E = 2.0 MeV	E = 14.0 MeV
Polyethylene	15	26	68
Borated Polyethylene	8	22	64
Al	269	257	266
Fe	98	138	151

Neutron background

The natural fast neutron background in the open environment is very low. Neutrons can be generated by cosmic muon induced spallation reactions in the soil and atmosphere. The typical muon flux at the surface of the earth is approximately 100 muon/m^2/sec, and the associated fast neutron flux is about a factor 10 lower. If the interrogating neutron source is pulsed, most of the natural background can be gated out, reducing the effective natural neutron flux to less than 1 neutron/m^2/sec. With a short measurement time, even a small number of returned fast neutrons can indicate the presence of SNM. No other material can produce fast neutrons when using medium energy neutrons as an interrogation tool. The threshold for (γ,n) reaction on most materials is out of energy range for natural occurring radioactive elements. The very few materials with low neutron producing reaction thresholds can easily be detected by other means.

Calibration

Since the medium energy neutron interrogation technique is exclusively sensitive to actual SNM nuclei, there is no substitute available for testing and calibrations. This raises an interesting problem that one needs actual SNM material to test the operational performance of the detection system. But low enriched SNM material (even a significant amount of D-38 at 0.3% U235, will contain enough U-235 to be useful) is sufficient to test and calibrate the detection system.

Conclusions

We have developed a working system for active neutron interrogation by selecting a reaction that is very exclusive to the detection of SNM and is not compromised by natural background reactions. 60 keV neutrons can penetrate all cargos of interest quite efficiently. The exception is cargo with a high hydrogen content, but X-rays can easily penetrate such cargo, and SNM would show up either through passive measurements or as a very substantial, high Z shield in the midst of bulk hydrogenous material. Fast neutrons are only produced by SNM material, normal cargo does not produce any background. Detecting fast neutrons on both sides of the cargo gives a clean signal, where the detection of even a few dozen beam times correlated fast neutrons is enough for a clean detection. We have demonstrated that the fast neutron detection system is insensitive to the interrogation medium energy neutron beam. This allows us to measure the fast neutron return signal while the interrogation beam is on, using the full intensity of the fast fission neutrons produced. The system is insensitive to ^{238}U and Thorium that is always present in significant amounts in all materials. It is also insensitive to all other non-SNM material. Used in conjunction with passive measurements and low dose radiography, this technique can assure a very high detection probability with an acceptable false alarm rate and can form one leg of an inspection regime flexible enough to be applied to essentially all incoming commerce regardless of form factor.

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